

Optimizing a Flexible Packaging Plant using Building Automation Systems (BAS)

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ABSTRACT

The flexible packaging industry, driven by demands for customization, sustainability, and efficiency, faces significant operational challenges including high energy consumption, process variability, equipment downtime, and waste generation. This research explores the integration of Building Automation Systems (BAS) into flexible packaging plants as a solution to these issues. BAS, comprising interconnected hardware and software systems, offers real-time monitoring, intelligent control, and predictive maintenance across various subsystems such as HVAC (Heating, Ventilation, and Air Conditioning), lighting, and machinery. The study outlines how BAS can significantly optimize energy use by dynamically adjusting environmental controls and production loads, thus reducing peak energy charges and supporting renewable energy integration. Furthermore, BAS enables precise control of material usage and minimizes production waste through advanced sensors, machine learning analytics, and system interoperability. Safety and maintenance protocols are enhanced via predictive risk management and automated response systems, mitigating hazards and ensuring regulatory compliance. Despite notable implementation challenges—such as legacy equipment compatibility, workforce resistance, and integration complexity—BAS emerges as a pivotal enabler of Industry 4.0 for packaging operations. The paper concludes by emphasizing the need for customized BAS solutions and further research to document successful case studies, ultimately fostering smarter, safer, and more sustainable manufacturing ecosystems in the flexible packaging sector.

Keywords: Flexible Packaging; Building Automation Systems; Energy Efficiency; Industry 4.0; Predictive Maintenance; Waste Reduction; Smart Manufacturing

INTRODUCTION

The flexible packaging industry is a dynamic and rapidly growing sector within the global packaging

market, characterized by its use of materials such as plastics, paper, aluminum foil, and biodegradable films to create lightweight, durable, and customizable packaging solutions. This industry caters to a wide range of sectors, including food and beverage, pharmaceuticals, personal care, and household products, driven by the increasing demand for convenience, sustainability, and cost-effectiveness (1).

The flexible packaging market has shown significant growth in recent years. According to a report from Grand

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View Research, the global flexible packaging market size was valued at \$248.3 billion in 2021 and is expected to grow at a CAGR of 4.7% from 2022 to 2030. This growth is attributed to factors such as increasing demand for packaged food and beverages, rapid urbanization, and the growing preference for more sustainable packaging alternatives (2).

Sustainability has become a central focus in the industry, with growing consumer and regulatory pressure to reduce plastic waste and adopt eco-friendly alternatives. This has led to innovations in recyclable, compostable, and bio-based materials, as well as increased investment in circular economy initiatives (European Flexible Packaging Industry, 2023). However, challenges such as recycling infrastructure limitations and the complexity of multi-material laminates remain significant hurdles (3).

Geographically, Asia-Pacific dominates the flexible packaging market, driven by rapid urbanization, a growing middle class, and increasing demand for packaged goods in countries like China and India (4). North America and Europe follow closely, with a strong emphasis on sustainable packaging solutions and stringent regulatory standards. The industry is under pressure to improve recycling rates and reduce its overall environmental footprint (5). This is why automation is important in this industry.

EVOLUTION OF AUTOMATION IN FLEXIBLE PACKAGING PLANTS

The origins of automation in flexible packaging plants can be traced back to the mid-20th century, coinciding with the rise of mass production and the development of PLCs (programmable logic controllers) in the 1960s. Early automation efforts focused on mechanizing repetitive tasks, such as cutting, sealing, and labeling, to reduce reliance on manual labor and increase consistency (10). These initial systems were relatively simple, with limited integration between machines and minimal data collection capabilities.

By the 1980s and 1990s, the advent of computer numerical control (CNC) and more sophisticated PLCs allowed for greater precision and flexibility in packaging machinery. This period also saw the introduction of supervisory control and data acquisition (SCADA) systems, which enabled centralized monitoring and control of production lines (11). These advancements facilitated the production of more complex packaging designs and improved the ability to meet diverse customer requirements.

The 21st century has ushered in the era of Industry 4.0, characterized by the integration of cyber-physical systems, the Internet of Things (IoT), and artificial intelligence (AI) into manufacturing processes. In flexible packaging plants, this has led to the development of smart machines that can communicate with each other, self-optimize, and predict maintenance needs (12). For example, modern automated systems can adjust parameters in real-time to accommodate variations in material properties or environmental conditions, ensuring consistent product quality.

Some key drivers of automation in flexible packaging plants are –

- **Demand for Customization:** The growing consumer preference for personalized and sustainable packaging has driven the need for flexible and adaptive automation systems.
- **Energy Efficiency and Sustainability:** Automation has enabled more efficient use of materials and energy, reducing waste and supporting environmental sustainability goals.
- **Regulatory Compliance:** Stricter regulations on food safety and packaging standards have necessitated the adoption of automated systems to ensure traceability and compliance.

BUILDING AUTOMATION SYSTEMS

Building Automation Systems (BAS), also known as Building Management Systems (BMS), are centralized, interconnected networks of hardware and software that monitor and control a building's mechanical, electrical, and plumbing systems. These systems are designed to enhance the operational efficiency, safety, and comfort of buildings while reducing energy consumption and environmental impact. BAS typically manage heating, ventilation, and air conditioning (HVAC), lighting, security, fire alarms, and other critical systems, often integrating them into a single platform for streamlined management (6).

In essence, a BAS integrates various subsystems within a building through a central control platform, which enables real-time monitoring and data-driven decision-making. For example, HVAC systems can adjust temperature settings based on occupancy, while lighting systems can be programmed to operate only when needed, reducing energy waste. This integration not only improves the comfort and safety of building occupants but also significantly lowers operating costs by optimizing energy use (9).

The adoption of BAS has grown significantly in recent years, driven by advancements in Internet of Things (IoT) technologies, data analytics, and the increasing demand for energy-efficient and sustainable building practices (7). By leveraging real-time data and automation, BAS enable facility managers to optimize building performance, predict maintenance needs, and respond promptly to operational issues. Furthermore, BAS play a pivotal role in achieving green building certifications, such as LEED (Leadership in Energy and Environmental Design), by ensuring compliance with energy efficiency standards (8).

A BAS is a distributed system oriented to the computerized control and management of building services, also referred to as building automation and control system (BACS) (13). The architecture of this distributed system can be organized into three layers (14) -

- The lowest layer is known as the Field Layer where the interaction with field devices (sensors, actuators) happens,
- the middle layer is the Automation Layer, where measurements are processed, control loops are executed and alarms are activated,
- the top layer is the Management Layer, where activities like system data presentation, forwarding, trending, logging, and archival take place

Modern BAS tends to separate the automation logic from the user interface through service-oriented abstractions, providing flexible access to the BAS from several different platforms and locations (15).

Hardware of Building Automation Systems

The setup of a BAS comprises actuators, sensors and hardware modules. Actuators react to signals closing circuits or varying the intensity of electric loads, which are physical devices such as a window blind or a ceiling lamp. Sensors are devices that convert a physical reality into a signal that can be measured. Although, some devices fit in both groups due to their sensing and actuating capabilities, for simplicity they may be perceived as two different virtual devices: one device capable of sensing and another one capable of actuating. In turn, actuators are often confused with electrical loads or with the physical device they drive, for example, what is commonly understood as a blind actuator is indeed a motor actuator (attached to a blind). Finally, actuators and sensors are attached to I/O ports of hardware modules that produce electric signals according to digital output commands and create readings from input signals.

The interaction between devices must be orchestrated through some type of control logic. Such logic lies in

components known as controllers. In building control systems, a controller usually consists of an application-specific hardware with embedded software that continually controls physical actuators (such as lights, blinds, among others) depending on the feedback given by monitored inputs (such as light or occupation sensors) or by receiving commands from the system. These devices can be either centralized (a single controller manages and monitors multiple building sub-systems) or decentralized (multiple controllers handle individual subsystems or even specific areas within the building), depending on the structure of the system. (15). Depending on the sophistication of the control functions controllers can be distinguished as Programmable Logic Controllers (PLC) or Direct Digital Controllers (DDC). PLCs typically implant simpler and more rigid functions that require little or no configuration, while DDCs are more flexible and typically implement functions that require extensive configuration such as scheduling or scenario management. Control functions can also be implemented in non-embedded software running in a server, thus centralizing the control functions of the BAS in the management layer, where the control logic can make use of aggregated data from different fieldbus segments. The advantage of a software controller is that it may undertake more complex decisions or explore additional information gathered from the system. (16)

With respect to a BAS, devices have two interfaces, an electrical interface, that defines how to connect the device to the rest of the system, and an application interface that enables other devices and software applications to interact with the device through exposed datapoints. Software device drivers consist of application programming interfaces used to enable other applications to interact with devices. These device drivers are used to-

- convert electric signals into values stored in variables or objects that can be read by software applications, and
- in contrast, they also convert values into electric signals that drive actuator devices.

Software of Building Automation Systems

The communication network is the backbone of the BAS, facilitating the transfer of data between the various components, including sensors, controllers, actuators, and the central control system. Modern BAS rely on digital communication protocols that enable seamless integration and interoperability of devices from different manufacturers. A common protocol is BACnet -

Building automation and control networking protocol (BACnet) was developed by a project committee established

by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (6). Its main objective was to provide a solution for BAS of all sizes and types. In 1995, BACnet was published as ANSI/ASHRAE 135 standard and later became a CEN and ISO standard within the ISO 16484 series (17). Overall, BACnet defines an information model that organizes the system devices using a standard collection of objects (14). These objects represent application services along their inputs and outputs, such as devices, calendars and schedules, commands, and control loops. In BACnet a device is represented by a device object which defines device properties like device model name, device vendor, device status and the list of other BACnet objects associated to the device. For example, a device with two analog inputs will have two instances of analog input objects associated (13). BACnet's model also accommodates proprietary object types for manufacturers to register functionalities not covered by standard objects, risking the interoperability between devices. BACnet commands are used to write to several attributes of a group of objects simultaneously when invoked. These objects can be devices, calendars, inputs, outputs. BACnet commands can be represented as objects containing a list of actions that can be executed, where each action consists of a list of attributes of other objects to be changed along with their new values. For example, a command object can define a set of attributes to modify when a certain room is unoccupied and another different set of attributes when it is occupied, hence defining two possible scenarios for that room, one called "occupied" and the other called "unoccupied".

Cloud computing is increasingly used in BAS to store and analyze large amounts of data. With cloud integration, BAS can offer remote access and control, which is especially beneficial for facility managers overseeing multiple buildings or campuses (9).

FLEXIBLE PACKAGING PROCESS

The first step in the flexible packaging process is the selection of the appropriate materials. The materials chosen depend on the product to be packaged, the desired shelf life, and the environmental factors to be considered. These materials can be used in single layers or in multi-layer structures for enhanced barrier properties. The choice of material is a critical factor in determining the functionality and appearance of the packaging.

The next step is extrusion or casting. Extrusion involves feeding plastic pellets (such as polyethylene, polypropylene, or polyester) into an extruder, where they are heated and melted. Once the material reaches the

desired temperature, it is forced through a die to form a continuous sheet of film. The material is then cooled and wound onto large rolls for subsequent processing. There are two primary types of extrusion processes used in flexible packaging: cast extrusion and blown film extrusion.

- **Cast Extrusion:** This process produces a flat, uniform film by extruding the molten polymer onto a flat surface, where it is cooled rapidly. Cast film is typically more transparent and has better dimensional stability, making it ideal for high-clarity applications (19).
- **Blown Film:** In this process, the molten polymer is extruded through a circular die and inflated to form a tube. This creates a film with enhanced strength and barrier properties. Blown films are commonly used for products requiring high puncture resistance, such as food packaging.

Once the base film has been created, the next critical stage is printing. Printing enables branding, product information, and decoration, making it an essential part of flexible packaging. The print quality of flexible packaging plays a significant role in consumer appeal, which can influence purchase decisions. Several printing methods are used in the production of flexible packaging:

- **Flexographic Printing:** This is the most common printing method used in flexible packaging. It uses flexible photopolymer plates to transfer ink onto the substrate. Flexographic printing is capable of printing on a wide range of materials, including plastic films, paper, and foil. It is highly suitable for high-volume production and provides fast-drying, vibrant colors, which makes it ideal for consumer packaging applications (20).
- **Rotogravure Printing:** Also used for high-volume printing, rotogravure uses engraved cylinders to transfer ink onto the substrate. While this method produces high-quality images and fine details, it requires a significant initial investment due to the cost of engraving the cylinders. It is ideal for products with complex graphics and is often used for flexible packaging applications that require high image quality and precise color reproduction (21).
- **Digital Printing:** Digital printing is an emerging method for flexible packaging. It uses digital files and inkjet or laser technology to print directly onto the substrate. This method is ideal for short-run or customized packaging due to its quick turnaround time, lack of need for printing plates, and ability to produce high-quality prints on demand (21).

After this, the next crucial step is coating. Coating is a vital step in flexible packaging production, designed to enhance the protective, functional, and aesthetic qualities of the packaging. Coatings can improve the packaging's resistance to moisture, oxygen, or other external environmental factors, and they can also contribute to the overall appearance of the packaging. The most prevalent coating techniques are –

- **Barrier Coatings:** These are applied to provide protection against moisture, oxygen, or UV light, depending on the product being packaged. For instance, barrier coatings are often used in food packaging to prevent spoilage by extending the shelf life of the product. Materials such as aluminum oxide and silicon dioxide are commonly used for these coatings (19).
- **Gloss or Matte Coatings:** These coatings are used for aesthetic purposes. Gloss coatings add a shiny, reflective finish to the packaging, which enhances its visual appeal. Conversely, matte coatings provide a soft, non-reflective finish that can give packaging a premium, sophisticated appearance.
- **Anti-fog Coatings:** These coatings are applied to packaging for perishable products such as fresh produce. Anti-fog coatings reduce condensation on the packaging, ensuring that the product remains visible and the packaging remains clear, even under humid or cold storage conditions.

The next process is laminating. Lamination is a process used to combine two or more layers of material into a single, multi-layer structure. Laminating enhances the strength, durability, and barrier properties of flexible packaging. This is especially important for products that require added protection against moisture, light, air, or contaminants. A few types of laminating methods are –

- **Solvent-based Lamination:** This involves applying a liquid adhesive to one layer, which is then bonded to another layer under pressure. This method provides strong adhesion and is commonly used for high-barrier packaging.
- **Solvent-free Lamination:** In this process, high-performance adhesives are used to bond layers together without the use of solvents. It is more environmentally friendly and is often used in food packaging to reduce the risk of solvent residues.
- **Extrusion Lamination:** Here, a layer of molten polymer is applied to one substrate and then bonded to another material. This method is used when additional barrier properties or strength are required (19).

After lamination, the next process is slitting, which involves cutting the wide sheets of film into narrower rolls. These smaller rolls are then ready for the next stages of packaging production. Slitting is necessary for creating film of the desired width for bags, pouches, or other packaging formats. During slitting, the film is passed through rotary blades or knives, which cut the film into specific dimensions. The precision of the slitting process is important to ensure that the film is of the correct size for the final packaging format, whether that be stand-up pouches, side-seal bags, or other configurations (20).

The final stage in the flexible packaging process is packaging, where the prepared films are converted into the desired packaging formats. This includes –

- **Bag Making and Pouch Formation:** In this stage, the slitted film is shaped into the final packaging format. For instance, stand-up pouches are formed by folding, sealing, and adding a bottom gusset to the film. This stage often involves additional processes, such as the addition of zippers or spouts for convenience.
- **Sealing:** Heat sealing is the most common method used to seal flexible packaging, where the edges of the packaging material are heated and pressed together to form a strong bond. This ensures that the product remains secure and protected from external contaminants.
- **Final Inspection and Quality Control:** Before the final product is shipped to customers, it undergoes rigorous inspection and quality control. This includes checks for dimensional accuracy, visual defects, and the integrity of seals.

A flexible packaging process flowchart will help understand the working of a plant (Figure 1).

Operational Challenges in Flexible Packaging

The flexible packaging industry is energy-intensive, particularly during key production stages such as extrusion, printing, and lamination. The high energy demand is largely driven by the heating, cooling, and mechanical processes required for material production, film extrusion, and the drying of inks and coatings. High energy consumption directly leads to increased production costs, which can erode profit margins. The energy requirements for extrusion and other stages like drying in printing processes often represent a significant portion of operational costs (22). As energy prices fluctuate, businesses may find themselves less competitive, particularly when price-sensitive products are involved. The industry's carbon footprint is also a concern. With growing emphasis on sustainability, companies are under

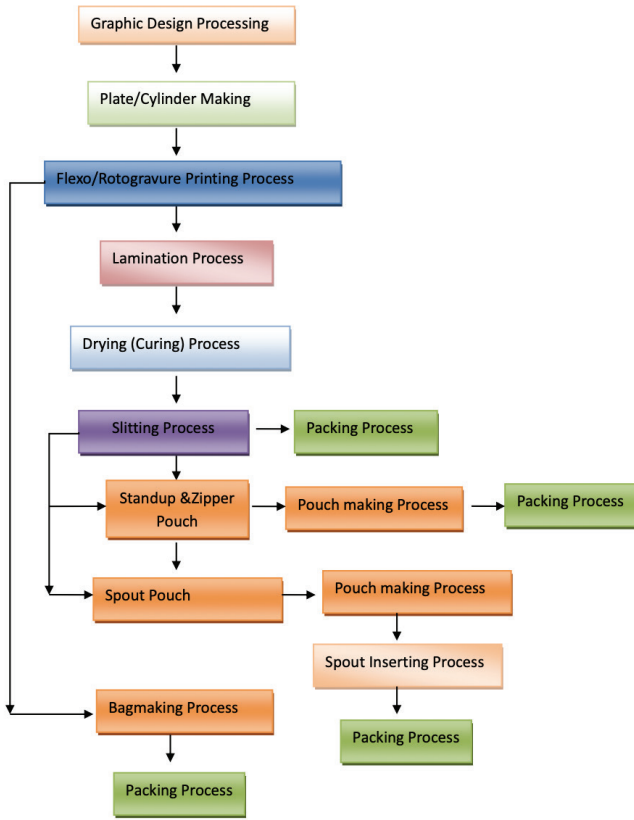


Figure 1. This flowchart outlines the complete manufacturing process of flexible packaging materials, starting from graphic design processing and plate/cylinder making. It includes the advanced printing technique of rotogravure printing, followed by lamination and drying (curing) to ensure durability and quality. The material is then slit and processed into different pouch types such as stand-up, zipper, and spout pouches through specialized pouch-making and spout inserting steps. The cycle concludes with bag making and multiple packing stages to prepare the final product for distribution (18).

increasing pressure from regulators, consumers, and stakeholders to reduce their energy consumption and adopt greener technologies. Failing to do so may lead to reputational damage and loss of market share (25).

Unplanned downtimes are a significant operational challenge for the flexible packaging industry. These downtimes can arise from a variety of sources, including machine failures, maintenance issues, material shortages, and operator errors. This is particularly critical in a highly competitive industry where fast turnaround times and meeting delivery schedules are essential for maintaining

customer satisfaction (23). Frequent machine breakdowns or failures result in higher maintenance costs and the need for more frequent repairs, which add to operational expenses. These costs, coupled with the costs of spare parts and labor, can become a substantial burden on the business (24).

Poor process control is another significant operational challenge in the flexible packaging industry. Inconsistent manufacturing processes lead to variations in the quality of the final product, which can affect product performance and customer satisfaction. Variations in film thickness, sealing strength, and print quality are just some examples of poor process control that can result in waste, rework, and customer complaints.

In the flexible packaging industry, the need for continuous quality assurance (QA) is paramount. Ensuring that every batch of packaging meets the specified standards for performance, safety, and aesthetics is critical, especially for industries such as food and pharmaceuticals, where packaging plays a significant role in protecting the product. For certain applications, particularly in food and pharmaceuticals, packaging must meet strict regulatory requirements regarding safety and performance. Failure to maintain quality assurance standards can result in non-compliance, leading to potential fines, recalls, or lawsuits.

Benefits Of Bas in Optimizing Flexible Packaging Plants

Energy Efficiency. One of the primary functions of BAS in flexible packaging plants is real-time energy monitoring. BAS can collect data from various energy-consuming systems, such as extruders, chillers, compressors, and lighting, through sensors and meters. This data provides plant managers with a comprehensive view of energy usage patterns, enabling them to identify inefficiencies and areas for improvement. For example, BAS can track the energy consumption of extrusion machines, which are among the most energy-intensive equipment in flexible packaging plants. By analyzing this data, operators can determine whether machines are operating at optimal efficiency or if adjustments are needed to reduce energy waste (27). Moreover, BAS can integrate with advanced analytics platforms to provide actionable insights. Machine learning algorithms can analyze historical energy data to predict future consumption trends and recommend energy-saving measures. For instance, if a BAS detects that a particular machine consumes excessive energy during startup, it can suggest preheating strategies or equipment upgrades to mitigate this issue (26). This level of granular monitoring

and analysis is crucial for flexible packaging plants, where even small improvements in energy efficiency can lead to significant cost savings.

Heating, ventilation, and air conditioning (HVAC) systems are essential for maintaining the controlled environments required in flexible packaging plants. However, these systems are often major energy consumers. BAS can optimize HVAC operations by adjusting temperature and airflow based on real-time conditions. For example, if a production area is unoccupied, the BAS can reduce airflow or switch to energy-saving modes, thereby conserving energy without compromising product quality (6). In addition to HVAC, process cooling systems, such as chillers and cooling towers, are critical for maintaining the temperature of extruders and other equipment. BAS can monitor the performance of these systems and adjust cooling loads based on production demands. For instance, during periods of low production, the BAS can reduce the cooling capacity to match the lower heat load, thereby minimizing energy consumption. This dynamic adjustment ensures that cooling systems operate efficiently, reducing energy waste and extending equipment lifespan (28).

Flexible packaging plants often face high energy demand charges, which are based on peak energy usage during specific periods. BAS can help manage these charges by implementing demand response strategies. For example, the system can shift non-critical processes, such as cleaning or maintenance, to off-peak hours when energy costs are lower. Additionally, BAS can prioritize energy usage by temporarily reducing the power consumption of non-essential equipment during peak demand periods. This load-shedding approach not only reduces energy costs but also helps plants participate in utility demand response programs, which offer financial incentives for reducing energy consumption during peak times (29).

As the flexible packaging industry moves toward sustainability, many plants are incorporating renewable energy sources, such as solar panels and wind turbines, into their energy mix. BAS can play a crucial role in integrating these renewable sources with traditional energy systems. For example, the system can monitor the availability of solar energy and adjust plant operations to maximize its use. During periods of high solar generation, the BAS can increase the use of electric-powered equipment, such as extruders, while reducing reliance on grid electricity. (30).

Waste Reduction. Flexible packaging production involves multiple stages, each with the potential for material inefficiencies and waste generation. Some problems include –

- **Material Inefficiencies:** Overuse or improper handling of raw materials, such as polymers, inks, and adhesives, can lead to unnecessary waste.
- **Process Variability:** Inconsistent process conditions, such as temperature, humidity, and machine settings, can result in defective products that must be discarded.
- **Equipment Malfunctions:** Malfunctioning equipment, such as extruders or laminators, can produce substandard output, increasing scrap rates.
- **Lack of Real-Time Monitoring:** Without real-time data on material usage and waste generation, it is difficult to identify inefficiencies and implement corrective measures.

Building Automation Systems (BAS) can play a transformative role in optimizing raw material usage in flexible packaging plants. By leveraging real-time data and advanced control mechanisms, BAS ensures that materials are used efficiently and effectively. Here's how BAS achieves this:

BAS can integrate with sensors and meters to monitor the consumption of raw materials such as polymers, inks, and adhesives. For example, flow meters can measure the amount of polymer resin fed into extruders, while ink sensors can track ink usage in printing processes. This data is transmitted to the BAS controller, which analyzes it to identify trends and anomalies. By providing real-time insights into material consumption, BAS enables plant operators to detect overuse or inefficiencies. For instance, if the system detects that a particular extruder is consuming more resin than expected, it can alert operators to investigate and address the issue (27).

BAS can optimize process parameters such as temperature, pressure, and speed to ensure efficient material usage. For example, in extrusion processes, the system can adjust the temperature and screw speed to minimize material waste and improve product quality. Similarly, in printing processes, BAS can control ink viscosity and application rates to reduce ink consumption and prevent defects. By maintaining precise control over process parameters, BAS ensures that raw materials are used optimally, reducing waste and improving product consistency (26).

BAS can integrate with production equipment to further enhance material efficiency. For example, the system can communicate with extruders to adjust material feed rates based on real-time production demands. It can also coordinate with printing presses to optimize ink usage for different packaging designs. This level of integration ensures that materials are used efficiently across all stages

of production, minimizing waste and maximizing output (28).

Equipment malfunctions are a major source of material waste in flexible packaging plants. BAS can address this issue through predictive maintenance, which uses data from sensors to identify potential equipment failures before they occur. For example, if the system detects abnormal vibrations or temperature fluctuations in an extruder, it can alert maintenance personnel to inspect and repair the equipment. By preventing unexpected breakdowns, predictive maintenance ensures that equipment operates reliably, reducing material waste and improving production efficiency (31).

BAS can integrate with sensors and meters to monitor waste streams such as scrap material, defective products, and process byproducts. For example, weight sensors can measure the amount of scrap generated by extruders, while vision systems can detect defective products in printing and lamination processes. This data is transmitted to the BAS controller, which analyzes it to identify trends and anomalies. By providing real-time insights into waste generation, BAS enables plant operators to detect inefficiencies and implement corrective measures. For instance, if the system detects a sudden increase in scrap material from a particular extruder, it can alert operators to investigate and address the issue (27).

BAS can leverage advanced data analytics to identify patterns and correlations in waste generation. For example, the system can analyze historical data to determine whether certain process conditions or equipment settings are associated with higher waste levels. Based on this analysis, BAS can recommend adjustments to reduce waste. For instance, if the system identifies that higher extrusion temperatures are correlated with increased scrap rates, it can recommend lowering the temperature to minimize waste (26).

BAS can integrate with waste management systems to track and manage waste streams more effectively. For example, the system can communicate with scrap conveyors and recycling equipment to ensure that waste materials are handled efficiently. It can also generate reports on waste generation and recycling rates, providing valuable insights for sustainability initiatives. This level of integration ensures that waste materials are managed responsibly, reducing environmental impact and supporting sustainability goals (28).

BAS can provide real-time alerts and notifications to operators and maintenance teams. For example, if the system detects a sudden increase in waste generation, it can send an alert to the plant manager's smartphone

or computer. This allows for immediate corrective action, minimizing the impact on production efficiency. Additionally, BAS can generate reports on waste generation, equipment performance, and material usage. These reports can be used to identify trends, optimize processes, and demonstrate compliance with regulatory standards (31).

Mitigating Safety Hazards and Maintenance Schedules

Safety is paramount in any manufacturing environment, and flexible packaging plants are no exception. During the plant design and construction phases, safety considerations must be embedded within the overall layout and system design. A well-designed BAS can play a critical role in this process by ensuring that all potential safety hazards are anticipated and mitigated from the outset.

BAS integrate various systems, including environmental monitoring, fire suppression systems, lighting controls, and access control systems, into a centralized platform that allows real-time monitoring and control. This integration allows for early detection of safety risks such as improper air ventilation, insufficient fire suppression coverage, or unsafe electrical setups that could lead to accidents. According to a study by Akinci et al. (2009), the integration of BAS into construction projects allows for better coordination and real-time monitoring of construction progress, enabling early identification of risks before they become costly problems. Moreover, BAS can ensure that all safety protocols are adhered to by triggering automated alerts when safety systems such as emergency shutoff valves or gas detection sensors detect potential risks. For example, in flexible packaging facilities, where chemicals and volatile materials may be used, BAS can help prevent chemical spills, leaks, or the release of toxic fumes by automatically activating ventilation or evacuation procedures when safety thresholds are breached (32). This proactive approach to safety ensures that risks are identified early and mitigated before they lead to accidents.

Once the plant is operational, the importance of safety protocols and maintenance schedules cannot be overstated. Safety protocols must be continuously monitored and enforced, while maintenance schedules must be adhered to in order to prevent equipment failure and accidents. BAS can seamlessly integrate these elements into a single framework that ensures a safe working environment for all personnel. One of the key advantages of BAS is the ability to automate safety protocols. For example, BAS can manage fire alarm systems, ventilation systems, and emergency shutdown mechanisms in flexible packaging

facilities, ensuring that all systems work in harmony to minimize risk. Through sensors and actuators, BAS can monitor vital parameters such as temperature, humidity, pressure, and air quality, and adjust them automatically when needed to ensure that the plant operates within safe limits. According to Yang et al. (2017), the integration of smart monitoring and control systems into BAS can enhance safety in industrial environments by providing continuous real-time data on environmental conditions and equipment status (34).

In terms of maintenance, BAS plays a pivotal role in scheduling and tracking maintenance activities. Preventive maintenance is a critical aspect of reducing downtime and preventing equipment-related hazards in the flexible packaging industry. By integrating maintenance schedules into the BAS framework, plants can ensure that all necessary checks and maintenance procedures are performed on time, minimizing the risk of system failures. BAS can be programmed to trigger maintenance notifications when sensors detect that equipment is operating outside of safe parameters or when scheduled maintenance tasks are due. This automation of maintenance procedures not only ensures the safety of plant personnel but also reduces the risk of costly downtime and operational disruptions (33). Predictive risk management is an advanced approach that allows plant operators to foresee and address potential risks before they escalate into incidents. By analyzing real-time data collected from various systems throughout the plant, BAS can help identify emerging risks and optimize responses to prevent accidents or failures. In the context of flexible packaging operations, where machinery and automation play a key role, predictive risk management offers significant safety and operational benefits.

BAS can integrate predictive maintenance tools that use data from equipment sensors to assess the condition of machinery and predict when failure is likely to occur. For instance, in flexible packaging plants, packaging machines, mixers, and extruders must run without interruption to ensure production schedules are met. By utilizing data analytics, BAS can predict when these machines will require servicing or when certain components might fail based on factors such as temperature, vibration, and pressure readings. This predictive capability allows plant managers to address issues before they result in system breakdowns, reducing the risk of accidents and unplanned shutdowns (26). Furthermore, predictive risk management through BAS involves continuous monitoring of the plant's safety systems and environmental conditions. Machine learning algorithms within BAS can analyze

historical and real-time data to identify patterns that suggest an increased likelihood of incidents, such as fire, gas leaks, or equipment malfunctions. Once these patterns are recognized, the BAS can trigger preventative actions, such as adjusting ventilation or pressure systems, and alert operators to take corrective actions. This predictive capability is particularly valuable in the flexible packaging industry, where processes can be highly automated, and failure of a single machine can have wide-reaching safety implications for the entire production line (35).

Challenges And Barriers to Implementation of Bas in Flexible Packaging

Flexible packaging plants often use legacy machinery and systems that were not originally designed to be integrated into modern BAS. Older systems may lack the necessary sensors or communication protocols to connect to a centralized automation platform, requiring significant modifications or even complete replacements to integrate with the BAS. These integration challenges pose significant technical hurdles and can significantly delay the implementation process. The integration of new systems with legacy infrastructure can be technically complex and costly, especially when different types of equipment from various manufacturers are involved. According to a study by Sauter and Stegall (2019), integrating BAS with existing systems is one of the most common technical challenges faced by industries implementing automation technologies. Furthermore, ensuring that all systems communicate seamlessly can require custom programming, resulting in increased costs and longer timelines for deployment (36). Additionally, many flexible packaging plants rely on automated processes that use proprietary technologies and specialized machines, which may not be compatible with off-the-shelf BAS solutions. Custom integration and the need for specialized solutions can further drive up costs and increase the complexity of the project.

Another barrier to the implementation of BAS in flexible packaging plants is the resistance to change from employees and management. Many plant operators and employees are accustomed to existing systems and processes, and the prospect of shifting to a new, automated environment can be met with skepticism and reluctance. Employees may fear job displacement due to automation or may feel uncomfortable with the complexities of the new system (30). This resistance to change can hinder the smooth adoption of BAS and may require additional efforts in terms of change management and communication to address employee concerns.

Furthermore, the implementation of BAS requires a skilled workforce capable of managing and maintaining the system. However, the demand for qualified personnel with expertise in automation, control systems, and BAS integration often exceeds supply. Flexible packaging plants may struggle to attract and retain qualified technicians and engineers who are familiar with the complexities of modern automation systems. This skills gap can slow the adoption of BAS, as plant operators may face difficulties in recruiting and training the necessary talent to manage these systems effectively.

CONCLUSION

The advancement of digital technologies has ushered in the era of Industry 4.0, a paradigm shift characterized by the integration of cyber-physical systems, the Internet of Things (IoT), cloud computing, and big data analytics. As manufacturing facilities evolve to meet the demands of increased automation, energy efficiency, and flexibility, Building Automation Systems (BAS) are playing an increasingly important role in creating connected, smart manufacturing ecosystems. In the context of Industry 4.0, BAS not only optimize facility operations but also contribute to the broader network of interconnected devices and systems that facilitate smart manufacturing. The integration of Building Automation Systems (BAS) with IoT, robotics, and digital twins is central to the development of fully connected, autonomous manufacturing environments. These technologies work together to create a highly responsive, efficient, and flexible system that can optimize plant operations, reduce energy consumption, improve product quality, and minimize downtime. As manufacturing continues to evolve under the umbrella of Industry 4.0, BAS will remain a critical component in enabling the seamless connection between physical and digital systems, driving innovation, and enhancing competitiveness in the manufacturing sector.

However, to fully harness the potential of BAS in this sector, implementation must be approached strategically. First, plants should conduct a comprehensive audit of existing equipment and infrastructure to assess compatibility with BAS technologies. This allows for a phased integration plan that prioritizes critical systems like HVAC, extrusion, and printing for automation. Second, companies must invest in workforce training to bridge the skill gap in automation technologies. Upskilling operators and maintenance staff ensures smoother adoption and long-term system sustainability. Third, manufacturers should adopt modular, interoperable BAS platforms

that support open protocols such as BACnet, enabling integration across multi-vendor equipment and reducing vendor lock-in. By focusing on these targeted actions, flexible packaging plants can move beyond energy monitoring to achieve predictive intelligence, waste minimization, and agile manufacturing — making BAS not just a support system, but a competitive differentiator in a rapidly evolving industry.

Although Building Automation Systems (BAS) hold great potential to improve operational efficiency, sustainability, and product quality in flexible packaging plants, there remains limited research on their specific application in this sector. Several factors contribute to this gap, including the complexity of packaging processes, lack of data and case studies, and challenges in integrating BAS with modern manufacturing technologies. However, the evolving landscape of Industry 4.0 presents significant opportunities for further exploration in this field. Future research could focus on developing customized BAS solutions, integrating them with Industry 4.0 technologies, and documenting successful case studies to pave the way for wider adoption in flexible packaging plants.

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